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Analysis of Spaceborne GPS Systems

NASA Grant NAG-1-1969

Final Report

For the Period 12 September 1997 through 11 March 1998

Principal Investigator

Mario L. Cosmo

August 1998

Prepared for

NASA Langley Research Center

Smithsonian Institution
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SUMMARY

This is the Final Report for Grant NAG-1-1969 "Analysis of Spaceborne GPS Systems" prepared by Mario Cosmo, PI at the Smithsonian Astrophysical Observatory for NASA Langley Research Center.

The technical Monitor is Dr. Steven Katzberg. This report covers the activity from 12 September 1997 to 11 March 1998.

This report describes the analysis of the suitability of the Plessey-based GPS receiver for spaceborne tethers applications. The study mainly focused on software modifications of the GPSArcitect and the preliminary design of an antenna for spaceborne use.

1. Software modification of the Plessey's GPSArchitect

The design of the GPSArchitect frees the PC's processor from performing expensive calculations.

With the GPSBuilder, only a slight modification to the display or control routines could cause the receiver to crash or to gradually lose accumulations. The liability with the independent-processor design of the Architect is the limited user access to internal data.

One deficiency of the Architect's codebase is the lack of support for the RINEX file format. We have attempted to correct this problem by linking code from the GPSBuilder system into the Architect's codebase and modifying several files to ensure compatibility.

The RINEX2.C file from the Builder code was transferred, the missing function definitions and variable declarations in the Architect code were added, and the routine which transfers data across the dual serial link from the Architect to the PC was modified.

With the RINEX2.C file in place, the Architect's processor can generate a RINEX file internally. Then, the file can be transferred across the serial link using the TDisplay routine in the Architect code.

By writing a small DOS utility, GPSINFO (this could be later upgraded to a robust windows program), we can then store the incoming RINEX data onto the PC's disk.

Further work in this area will be performed in the future.

The general direction of code modifications are listed in Appendix A

2. GPS Receiving Antenna

2.1 Introduction

The purpose of our analysis is to use a GPS receiver on a tethered satellite to determine the satellite position, velocity and other kinematic information.

High-accuracy GPS imposes heavy restrictions on the receiving antenna electrical properties. However, when the antenna needs to be mounted on a tethered satellite, size, weight, mechanical characteristics, aerodynamic profile, ease of installation, and costs are, also, very important constraints. Consequently, the antenna design compels a trade off between the demanding electrical requirements and the more practical non-electrical ones.

The electrical requirements aim to the high-accuracy GPS positioning, while the non-electrical requirements, mostly mechanical or commercial, determine the feasibility of the project. In the following, we try to identify some of the most important constraints, both electrical and non-electrical.

2.2 Electrical Requirements

Multipath Reduction: The GPS receivers to be installed on tethered satellites are intended to provide sub-meter near-instantaneous kinematic information on the satellites. Because multipath represents a significant source of error in high-accuracy GPS positioning, it is necessary to use an antenna opportunely designed to reduce the reception of multipath signals. Therefore, the antenna pattern of a GPS receiving antenna should have the following characteristics:

- sharp pattern slope at low elevation angles, where most of the multipath reflections are received by the GPS antenna (slope > 1 dB/deg at 5 deg elevation).
- small back radiation to decrease the effects of the reflections of the GPS signal from the ground
- high cross-polarization rejection ratio (>15 dB), to reduce the reception of left-hand polarized reflected GPS signals

GPS signal reception:

- In order to obtain a good coverage of the signals from all the GPS satellites the antenna pattern of the receiving GPS antenna should be almost hemispherical (>130 - 140 deg). This implies that the gain should have a very low directivity.
- Because the GPS signal received is very weak, the antenna needs a good impedance matching.
- The variation of the radiation pattern over the main beam, especially near the zenith, should not exceed 6-7 dB.
- The receiving antenna is required to have a uniform group delay response for all angles of incidence in most of the upper hemisphere. This is to avoid that signals from satellites at different elevation angles experience timing errors.

Dual-Frequency Capability: Because the GPS satellites transmit signals at two frequencies, $L_1=1.575$ GHz and $L_2=1.227$ GHz, the receiving antenna should have either one of this two properties:

- large bandwidth (out-of-band interference might occur in this case).
- dual-frequency capability (most desirable case).

2.3 Non-electrical Requirements

Tether Satellite Motion: A tethered satellite is not an ideal platform for a GPS receiving antenna. Because significant dynamics might occur on time scales of a few minutes (e.g. lateral modes), a GPS antenna deployed on a tether satellite might experience very rapid motions. The GPS receiving antenna should be:

- not too sensitive to mechanical stress
- aerodynamic enough to remain unnoticed by the tether satellite kinematics during the mission.

Tether Satellite Size: A tethered satellite is usually a small satellite, which falls into the category of Micro-Satellites (between 10 kg and 100 kg). The GPS receiving antennas deployed on a tether satellite should, therefore, be

- small in size
- relatively light weight

2.4 Dual Band Circularly Polarized Aperture-Coupled Stacked Microstrip Antennas

A thorough bibliographical search [1] has been conducted to investigate different antenna designs. In a very recent paper by Pozar and Duffy [2], a better design of stacked-patch antennas was identified as very suitable for Spaceborne GPS applications [2]. A new feeding technique, a different dielectric material for the substrate and opportune patch dimensions, allowed the antenna to meet all the design requirements, both electrical and non-electrical.

A stacked-patch microstrip antenna is composed of three layers: a top patch on a dielectric substrate, a bottom patch on a dielectric substrate, and a feed substrate, as shown in fig. 1.

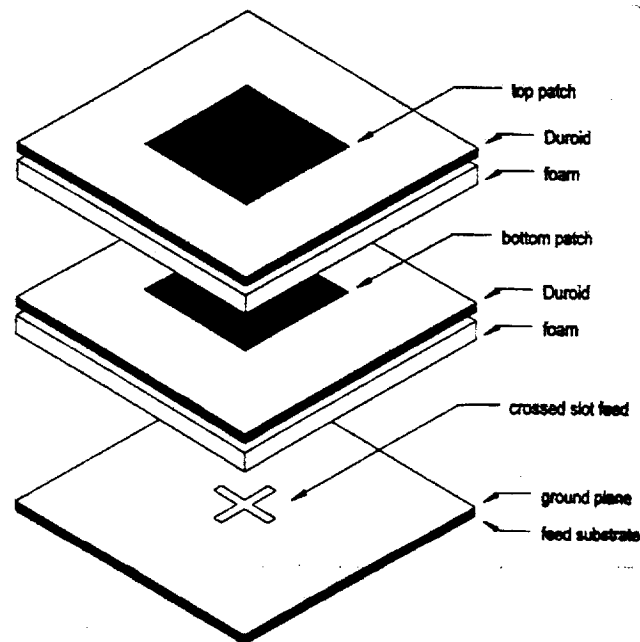


Figure 1. Geometry of the Aperture-Coupled Stacked-patch microstrip GPS Antenna

In the following we will try to clarify the different characteristics of this antenna design.

Dual-Band/Stacked. When the patch antennas are used for GPS applications, the designs at L1 and L2 can be combined into stacked patch antennas and adjusted to obtain the dual-frequency operation. The design described in [1] presents 40 MHz bandwidth (3%) at each GPS frequency, 1.227 GHz and 1.575 GHz.

Aperture-Coupled. Power can be coupled into or out of the antenna by a variety of methods that can broadly be classified into contacting and non-contacting. Contacting feeds involve the direct connection of a transmission line to the patch antenna. Non-contacting feeds use electromagnetic field coupling to transfer power between the feedline and the radiating patch.

Aperture coupled microstrip antennas exhibit some advantageous properties with respect to other feeding techniques. Non-contacting feeding, shielding of the feed network from the radiating aperture, and increase of the bandwidth with respect to the traditional patch designs, are all desirable features that make aperture coupling a very appealing feeding technique.

Because this feeding technique substantially increases the bandwidth, the entire GPS frequency range could be covered with a single aperture-coupled patch element. However, to reduce out-of-band interference, dual-band coverage of L1 and L2 obtained by using the stacked patch design was chosen.

Circularly-Polarized. The circular polarization is obtained by independently exciting two orthogonal linearly polarized modes of equal amplitude and 90 deg phase shift. This can be obtained from aperture-coupled elements by using off-center-coupling apertures or by using crossed slots.

The design of a dual-band circularly polarized aperture-coupled stacked microstrip antenna is complicated by the fact that there are at least 10 interacting design parameters to consider in addition to the microstrip feed network details. The resonance frequency, bandwidth, antenna pattern, back radiation, coupling, polarization, etc. all depend in a very complicated way on the following interdependent geometric parameters, shown in figure 2.:

- Top Patch Length, L_{TAT} and Top Patch Width, W_{TAT}
- Bottom Patch Length, L_{BAT} and Bottom Patch Width, W_{BAT}
- Top Antenna Substrate Dielectric Constant, ϵ_{TAT} and Thickness, T_{TAT}
- Bottom Antenna Substrate Dielectric Constant, ϵ_{BAT} and Thickness, T_{BAT}
- Aperture Length, L_{BAT} and Aperture Width, W_{BAT}

To simplify the design process a linearly polarized stacked-patch geometry using a single coupling aperture and a single centered microstrip feed line was, first, simulated. The substrate thickness and patch sizes

determined in this first step should be close to the values of the final circularly polarized design. The aperture size, on the contrary, is expected to increase when balanced feed lines are used.

The size of this design applicable to SGPS applications is relatively small:

1. $L_{bp} = 8.35 \text{ cm}^2$ for the squared bottom patch,
2. $L_{tp} = 7.90 \text{ cm}^2$ for the squared top patch
3. $T_{tot} = 1.43 \text{ cm}$ total thickness (0.635 cm for each substrate + 0.079 cm Duroid).

Both antenna substrates have a relative dielectric constant $\epsilon_r = 1.08$ and were made of “high-density Rohacell foam material with thin Duroid skins for the patch metallization” [2]. With this choice the antenna is very lightweight, the bandwidth is maximized for a given thickness and the material costs are low.

The measured antenna patterns at 1.227 GHz and 1.575 GHz (fig. 3a and 3b) show a broad main lobe, with a decrease of -10 dB at about 120-140 deg. The receiving antenna designed in [2] showed large antenna pattern. No information on the polarization rejection ratio is provided in the paper. However, reference [2] does provide information about the group delay response of the antenna as a function of the satellite incidence angle (in azimuth and elevation). Group delay is not very often used to characterize antennas, but is usually introduced for microwave components such as filters. In high accuracy GPS this parameter is very important to avoid timing errors in the GPS signals received at different incident angles. The antenna shows a good group delay response, which critically depends on the inherent symmetry of the antenna and its feed.

The lack of connectors in the feeding technique and the small sizes of this antenna (especially its thickness) makes this antenna very suitable for our application, since the tethered satellite is moving rapidly and the receiving antenna can be subjected to strong mechanical stress.

A back radiation lobe (up to 15 dB) can be observed. It is, therefore, desirable to introduce a lossy absorber material in the region below the feed layer.

From the literature search performed so far the dual-band circularly polarized aperture-coupled stacked microstrip antenna seems to be the antenna design that best meets the electrical and non-electrical requirements of a SGPS receiving antenna to be mounted on a tethered satellite.

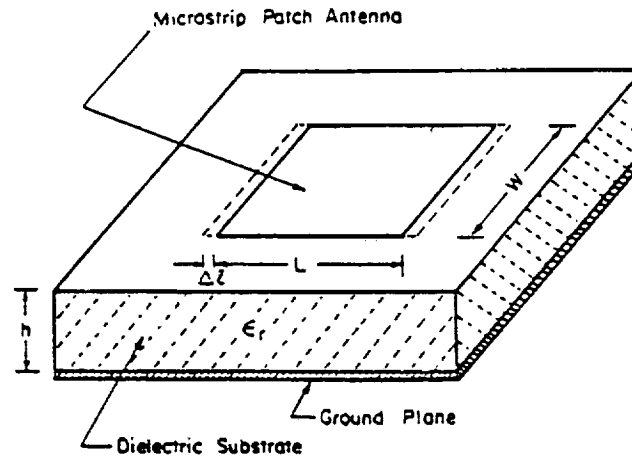


Figure 2. Microstrip Antenna basic geometry

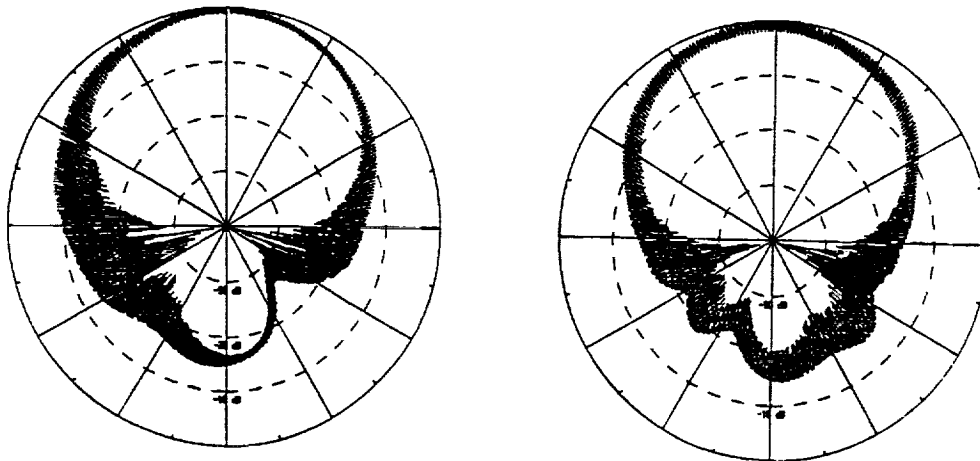


Figure 3a and 3b. Measured spinning linear patterns of the circularly polarized aperture-coupled stacked patch microstrip antenna at (a) 1.22 GHz and (b) 1.575 GHz (b)

2.5 Commercially available Antennas for SGPS applications

Because GPS can provide spacecraft positioning, orbit determination, relative positioning, attitude, clock synchronization, etc. in real-time, several missions have used or will use GPS receivers in space. (See the web site: <http://gauss.gge.unb.ca/grads/sunil/sgps.htm> for information on space missions that perform SGPS measurements).

Due to the difficulty to find literature relevant to commercial SGPS receiving antennas the following information were acquired mainly by e-mail and contacting personally the individual or group involved in the antenna design in each project. More information about antennas commercially available for SGPS applications will be collected in the future.

For the GPS/MET mission a receiving antenna manufactured by Ball Aerospace was used. It is a dual-frequency ceramic patch antenna, about 9 cm² by 1.5 cm high.

Trimble provided the antenna/LNA used on PoSAT-1. The overall size is about 10 cm². The antenna element is made of Teflon. The original antenna was taken apart and the elastomer-type soft rubber was replaced with wire mesh grounding strip. This measure was taken to prevent the vaporization of the rubber in vacuum.

For FASat, Micropulse ceramic-loaded plastic antenna elements are used, which are only about 5 cm². A separate LNA was used. To prepare the antenna for space it was necessary to disassemble and replace the cable.

2.6 Conclusions

A reasonable amount of literature can be found on the general topic of GPS receiving antennas, but very little has been published on spaceborne GPS receiving antennas. This very new topic seems to be so far more of interest for the industrial world than for the academic community.

For satellite applications, microstrip antennas are usually preferred over other types of antennas mainly because of their non-electrical characteristics, such as small size, relatively lightweight, shape, possibility of integration with microwave integrated circuits, and relatively low costs.

However, although the electrical performance of the basic microstrip antenna is generally very poor, it can be enhanced with innovative designs and configurations. Recently, the possibility to improve their electrical properties triggered the academic interest on microstrip antenna design for space applications. New feeding techniques, new dielectric materials for the substrate and a stacked-patches structure have overcome the most serious drawbacks of microstrip patch antennas (such as narrow band and feed losses).

Careful design of patch antennas could meet all the requirements (electrical and non-electrical) of a GPS receiving antenna to be mounted on a tethered satellite.

Based on this preliminary study the Dual-Band Circularly Polarized Aperture-Coupled Stacked microstrip antenna appears the most suitable existing antenna design to be used on tethered satellites for GPS applications.

We will, therefore, concentrate on this type of antenna, and we will perform a detailed analysis of its suitability to our project.

3. Additional Work

This study has also briefly analyzed the “cold-start” and acquisition issues.

A time-triggered start followed by an update of the constellations orbital elements seems the most promising approach.

The navigation information acquired at the last fix would be fed to an orbital propagator. We have used the FORTRAN version of the program SDP8, which is fast and reliable. The approach, however, could not be tested with the receiver data since we are still not able to retrieve RINEX and navigation files. Further work is planned in this area.

4. References

- [1] Francesca Scire' Scapuzzo, "Reference Search and Preliminary Analysis of Spaceborne GPS Receiving Antennas for Tethered Satellites", SAO Internal Report, February 1998.
- [2] D. M. Pozar and S. M. Duffy. "Dual-Band Circularly Polarized Aperture-Coupled Stacked Microstrip Antenna for Global Positioning Satellite" *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 11, pp. 1618-1625, Nov. 1997.

Appendix A. GPSArchitect Code Modifications

General Remarks

- Commented out code which once sent formatted data sentences over the serial link
- Will add routines to send out text chunks at each RINEX update
- Currently using NAV.C as a timing system for RINEX updates, but may change to DISPLAY.C - this may simplify coding. Since all serial transmissions take place in DISPLAY, this is the logical place for a RINEX update to be called.
- Adding code to DISPLAY.C to send RINEX data sentences over the serial link
- All modifications to original code preceded with /* modified MIH ... for searching purposes
- Necessary interface modification would be to add a new command to CMD.C
- Currently no way for the user to dynamically turn RINEX recording on and off
- Need to add new command processing routine, similar to the routine in the builder code, which starts and stops RINEX file recording.

Added file RINEX2.C -

- transferred from original GPSBuilder code
- updated missing function definitions and variable declaration in GLOBALS.C, PROTOS.H
- removed references to FILE pointers Rx2N, Rx2O these are no longer relevant when using GPSArchitect since architect has no internal file output capability
- the output that would have been directed to these pointers will now come through the TDisplay routine
- commented out all fprintf lines, writing to both RINEX files
- output now handled by output through TDisplay task
- functions currently called from Nav.c, but may be efficient to move them to Display.c

- no particular attachment of rinex output to navigation task
- builder uses it because of convenient TIC meas.
- include code in Display file that calls RINEX routines, checks for need of current RINEX output

Corrections in file NAV.C

- added routine to function GetNavFix line 296
- calls functions in RINEX2.C to send out observations from Builder code's NAV.C file
- at line 206 declared variables i, obspresent, sv as local variables to function GetNavFix. In original NAV.C these were global. New observation structure requires additional level of dereferencing
- routine moved to DISPLAY.C. DISPLAY.C is already synchronized to send out data once per second. This RINEX routine is placed here for continuity with the builder code, since old routine came from NAV.C.
Because output from architect must be synchronized with TDisplay task, no output can occur in NAV.C - this complicates the task, since the RINEX routines need to access to the SendString() command contained in DISPLAY.C
However, transferring RINEX routine to DISPLAY means rinex output is no longer exactly synchronous with navigational task. The data will stay the same long enough for recording with a RINEX routine.
- routine mostly transferred from RINEX2.C, with some modifications to account for some variable conversions, since time structure for Builder and Architect are different

Corrections in file POSTIME.C

- transferred function GpsTimeToGregorianDate from Builder Code at line 105 required by RINEX2.C file to calculate Greg. Date

Corrections in file GLOBALS.C

- added declarations for variables in RINEX2.C file at line 14 for:
a) Rx2TIC, time of next observation; b) Rx2Obsv, observation data; c) Rx2Lli, Lost lock indicators; d) Rx2Sigstr, Signal Strengths; e) Rx2NRecs, Rx2ORecs, file records

Corrections in file DISPLAY.C

- commented out code which sends formatted data sentences used by WINMON at line 92. We will add code to transmit RINEX-specific data sentences, one type for .N file, another for .O file. We will use data sentence format as defined by Architect code

Corrections in file PROTO.S.H

- added prototype definitions for functions used in RINEX2.C file at line 230:
 - a) Rx2IU, records ionospheric model and UTC conversion to .N file; b) Rx2EPH, records ephemeris data to .N file; c) Rx2OBS - records observables into .O file; d) Rx2Comment, record rinex comment; e) Rx2Start , begins rinex files; f) Rx2Stop ends recording of rinex files

GPSINFO.EXE

- usage GPSINFO <outfile>
- a small DOS utility which listens to the PC's serial port for incoming data sentences
- opens serial port, waits for start of a data sentence transmitted across the link to synchronize transmission/reception

This utility currently has no capacity to transmit commands to the GPS-Architect. We will need a new user interface to replace WINMON, since WINMON has no RINEX capability. A small utility like GPSINFO could be replaced with a more robust windows utility which had command transmission capability and a rudimentary file management system to keep track of which RINEX files were being written and updated.